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A low-cost three-dimensional sample collection array to evaluate and monitor constructed wetlands

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ABSTRACT

Artificially constructed wetlands are gaining acceptance as a low-cost treatment alternative to remove a number of undesirable constituents from water. Wetlands can be used to physically remove compounds such as suspended solids through sedimentation. Dissolved nutrients, biochemical oxygen demand, heavy metals, and potentially harmful anthropogenic compounds can all be removed in constructed wetlands through geochemical and biological processes. Sample collection to evaluate the effectiveness of treatment and to monitor the status of wetlands is usually only conducted at the inlet and outlet of the wetland due to cost constraints. To better understand the internal hydrology and biogeochemical processes operating within the wetland more intensive sampling is needed that does not interfere with the hydraulics of the system. A new relatively low-cost sample collection design has been developed using mostly off-the-shelf parts that allows for permanent, internal, three-dimensional sample collection in wetlands. The design has been used to construct a permanent three-dimensional array of 60-sample locations that can be sampled simultaneously throughout a 1.2 ha constructed wetland for less than US$ 5000. The sampling array was used in a tracer study and showed spatial and temporal differences in tracer concentration within the wetland. Concentration differences were seen and measured in all three dimensions. The basic features of the system are described and an example how to construct an array that can suit any wetland design is given.

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1. Introduction

Wetlands offer a biologically diverse ecosystem capable of removing many contaminants found in water. Artificially constructed wetlands are a low-cost treatment alternative for removal of a number of undesirable constituents found in waste streams from industry, mining, agriculture, and urban areas (August et al., 2002; Moustafa and Hamrick, 2000; Hambright et al., 1998; Guardo and Tomasello, 1995). Wetlands can be used for mechanical removal of suspended solids through sedimentation (Schmid et al., 2004). Dissolved nutrients, biochemical oxygen demand, heavy metals, and potentially harmful anthropogenic compounds can be removed in constructed wetlands through geochemical and biological processes (August et al., 2002; Drizo et al., 2000; Guardo and Tomasello, 1995; Hambright et al., 1998; Moustafa and Hamrick, 2000). Wetlands can also be used as a cost-effective final polishing step for municipal sewage effluent to insure discharged water meets stringent wildlife protection standards.

According to Buchberger and Shaw (1995), the two most important processes in determining the effectiveness of con-

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structed wetlands for water treatment are biological and hydrological dynamics. Biological dynamics are defined as the biogeochemical processes that remove contaminants from water being treated in a wetland. These processes are in turn linked temporally and spatially throughout the wetland via the hydrology of the system. The hydrology of the wetland determines the distribution and retention time of nutrients on which the biota depend, while nutrient concentrations are influenced by the metabolic processes of the biota. In addition, the presence of macrophytes can be critical in determining the flow dynamics of the wetland due to small-scale interruptions to flow paths created by things such as plant stems, which results in an increase in surface roughness (Schmid et al., 2004).

In the past, constructed wetlands were designed as a series of plug flow reactors connecting continuously stirred reactors. The vegetated areas were seen as plug flow reactors where flow is laminar and well mixed in the plane perpendicular to the flow (Keefe et al., 2004). Open water areas were viewed as continuously stirred reactors where the water is well mixed in all three dimensions. Using this conceptual framework the aspect ratio (the length of the wetland parallel to flow divided by the width perpendicular to flow) becomes critical. It was generally thought that the higher the aspect ratio the more ideally the wetland behaved, with the flow in the longitudinal direction being laminar and the volume of water perpendicular to the flow being well mixed. More recently it has been found that the assumptions of well mixed plug flow are faulty. Kadlec (2000) reported that, in a number of wetland tracer studies, flow through constructed wetlands was non-ideal and short-circuited flow paths were present. Short-circuiting was even found in lab-scale wetlands as small as 1 m long × 0.5 m wide × 0.5 m deep (Drizo et al., 2000).

Non-ideal flow through constructed wetlands is most often quantified using tracer experiments. Keefe et al. (2004) used a conservative tracer, bromide, and a reactive tracer, rhodamine WT, to characterize three different constructed wetlands with various seepage losses. They found that the volume of the wetland through which the tracer flowed ranged from 41 to 84% of the total wetland volume. Hydraulic short-circuiting resulted in retention times half of that predicted from the design, which can reduce potential treatment efficiency by more than 50%. Generally these studies reported the fraction of the wetland through which water flowed, but the actual physical location of that water was not determined due to the lack of internal sampling. Additionally, it has also been shown that the use of bromide as a tracer can be problematic due to the formation of density gradients and the loss of a significant mass of the tracer due to plant uptake (Schmid et al., 2004; Xu et al., 2004). Internal sampling would increase understanding of both the flow path through and stratification within the wetland being studied.

Tracer experiments in the field are usually conducted by measuring influent and effluent tracer concentration over time (Keefe et al., 2004). Studies to determine treatment effectiveness in constructed wetlands often only look at inflow and outflow concentrations (Peall and Shulz, 2001; Rostad et al., 2000). Sample collection within wetlands can range from simple grab samples to automated sampling systems that operate unattended 24 h a day. The cost of automated samplers is usually thousands of dollars, therefore the use of more than five or six of these samplers quickly become cost-prohibitive. Internal samples are often times limited to 4 or 5 locations (Shulz et al., 2003). In addition to the usefulness of internal sampling to determine flow characteristics, continued sampling is desirable to monitor the effectiveness of treatment within the wetland (Hernandez and Mitsch, 2007).

The cost-constraining feature of liquid sample collection from environmental samples is the pump that is used to move water from the sample location to the collection location. In general, two different pump types can be used. The first type of pump is one that draws air to create a pressure deficit that pulls the water into a collection vessel. This type of pumping scheme can be used to draw water to multiple collection vessels using a single pump connected by tubes that will not collapse under the pressure deficit. There are two main disadvantages of this method. Vacuum pumps are designed to move gas and thus need to be protected from liquid by traps that prevent liquid from entering the pump. For multiple sample collection locations the size of this liquid trap needs to be very large to ensure protection of the pump. The second drawback of this method is that a vacuum pump, capable of pumping sufficient air to maintain the pressure deficit needed to pull water from multiple sample locations, would be very costly.

The second pump type that can be used is one that is designed to move liquid which removes the need for a liquid trap. However, this type of equipment must pass the sample through the pumping mechanism, which limits the number of sample locations per pump to a single sample point so that cross-contamination of the samples does not occur. To sample from a number of locations the pump would have to be attached to each individual sample location, the sample collected, then disconnected and attached to the next location. This scheme would allow for spatial sampling but the samples would be temporally discrete and, therefore, the first sample collected could not be compared with a sample collected 30–60 min later. Additionally, the pump would have to be capable of very low flow rates so that during sample collection turbulence at the location where the sample was collected within the wetland could be minimized.

A low-cost sampling system is needed which can sample multiple points in an aquatic system with no cross-contamination between samples and can be built from readily available components. The purpose of this work was to design, build, and test a sampling system which overcomes the limitations of using either of the above schemes and to demonstrate that the array can be used for internal sampling of a large (1.2 ha) constructed wetland.

2. Materials and design

A sampling system was built using one large water pump which continually pumped water hydraulically separate from the wetland to be sampled (Fig. 1). The suction line of the pump had a nominal inside diameter of 7.6 cm. A reducing tee with a nominal inside diameter of 2.5 cm was installed prior to the pump. To this tee a PVC line was used to provide the suction ultimately needed to draw the sample from the wetland. A gate valve was installed between the main

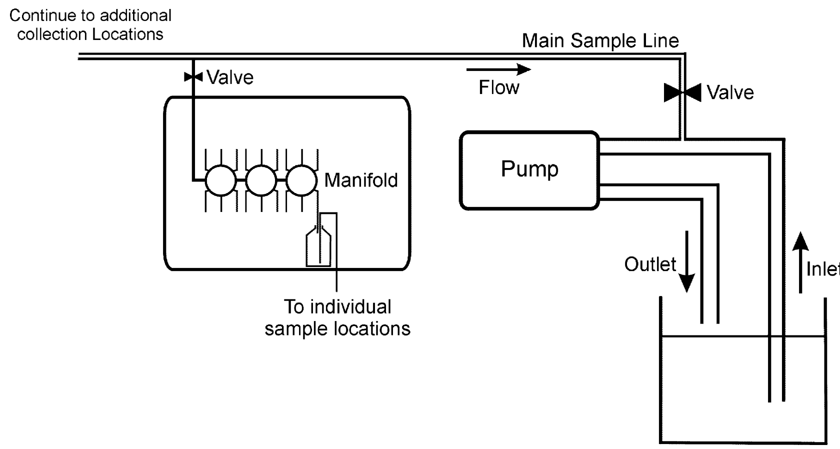

Fig. 1 – A schematic representation showing the basic components of the sample collection system. The pump intake and return is in the same sump. The main sample line is connected to the inlet side of the pump and can provide suction for a number of sample locations. Within each sample location the manifold will accommodate up to 18 individual sample locations. The entire sample line and each sample location can be isolated from the inlet of the pump.

sample line and the main pump suction line able to throttle the flow through the sample line. At each sample collection location a number of different sample collection bottles were connected to the main sample line through a manifold that combined all of the incoming flow from each individual sample collection bottle to a single line. When the valve between the sample line connected to the sample location was opened a pressure deficit was created and began to draw water from the wetland where it ran through the collection bottle and on to the main sample line ultimately through the pump. Samples pulled from the wetland were collected using individual sample lines from each collection bottle and terminating at a unique point within the wetland. The water was allowed to pass through a collection bottle, then to a manifold where the flow from other locations was combined into a common collection line that finally allowed all of the combined flow from different sample locations to enter the pump intake at the far end of the wetland. The pump discharge was simply returned to the sump where the inlet was drawing creating a circulation that required no additional water to provide for operation of the system other than the overflow from the sample collection bottles. The pump was capable of providing 7.5 m of lift at the inlet and 2.5 m of lift 200 m away at the point furthest from the pump.

Design of the manifold system, which allowed sample solutions to remain separate through each individual sample collection bottle and then combine to a common suction line, used off the shelf micro irrigation manifolds used in reverse. The manifold has a central supply connection that is split and connected to six individual valves. By connecting the supply point to the inlet of the pump via the main sample collection line (Fig. 1) and each individual port of the manifold to a sample collection bottle, the manifolds were operated such that water flowed from the sample bottle, in through the ports, and out of the common supply point then to the main sample line toward the water pump. The individual ports had valves and barbed fitting that were connected to plastic tubing made from low density polyethylene (LDPE). The LDPE tubing had a nominal outside diameter of 0.64 cm and a wall thickness of 0.1 cm. The plastic tubing was passed through one hole of a #3 two-hole stopper. The stopper was placed tightly in a 1-L Boston Round amber bottle. The other hole in the stopper had an end of plastic tubing passed through it that was continuous all the way to the sampling location within the wetland. The tube from the sample point in the wetland was pulled through the stopper so that it was at the bottom of the bottle when the stopper was in place. The tube that went to the manifold was cut such that it was near the top of the bottle within a few cm of the stopper. This arrangement meant that when the sample bottle was full it could continue to fill from the bottom and then exit from the top of the bottle resulting in a sample that was continually being renewed until all of the bottles were full, at which time all sample locations could be turned off simultaneously preserving temporal continuity.

The manifold and rack to hold collection bottles were placed inside of a large plastic storage box (Fig. 2) that could be left in the field and locked for security. The sample was collected through a stainless steel, cylindrical, ground water sampling screen 0.65 cm diameter × 15 cm long. The screen was equipped with a barbed fitting that would accept the plastic tubing. The screen on the sampling probe allowed water to freely enter but prevented large suspended solids from being sampled. To hold the sample screen in the wetland a frame was constructed using schedule 40 PVC pipe (Fig. 3). The frame was constructed so that it was rigid and could hold the sample screen horizontal to the surface and perpendicular to the direction of water flow. The sample screen was placed between two “tee” fittings that faced each other and a hole was drilled in the side of the PVC frame through which the plastic tubing was passed. The frame was constructed so that a rigid piece of steel rebar could be passed down inside of the pipe on each side of the frame and driven into the sediments. The use of PVC for the frame construction allowed for the placement of as many sample screens as needed at any depth within the water column. In addition, PVC is very resistant to the harsh conditions below the water surface in the wetland.

Fig. 2 – Basic design of the sample collection points is shown. A storage box was chosen that could withstand the weather and had enough room to accommodate the manifolds and sufficient collection bottles. The manifold is the series of three round objects in the lower left of the picture. Each port on the manifold is connected to a capped piece of PVC pipe by plastic tubing passing through a rubber stopper inserted into the PVC pipe. A second piece of plastic tubing passing through the stopper leaves through the bottom of the box and is connected to the sampling screen in the wetland. As configured the system is ready to be operated to flush the individual sample collection lines before sample collection begins. The capped PVC provides a smaller void volume to fill during flushing.

3. Field installation

The sampling array was installed and tested in cell one of the Hayfield site at the Trés Rios demonstration wetland at the 91st Ave. sewer treatment plant located in Phoenix, AZ. The wetland is a 1.2 ha constructed wetland that is being used to determine design parameters for a 260 ha full-scale treatment wetland. A general physical description of the wetland can be found in Table 1 and Fig. 4. The three-dimensional sample array was installed at 24 different locations within the wetland (Fig. 4). Twelve of the locations were in emergent zones approximately 30 cm deep. The remaining 12 locations were in deep-water zones 1 m deep. In the emergent zones there were three sample locations across the wetland and two sample depths at 5 and 25 cm below the water surface. In the deep zones there were three sample locations across the wetland and three depths were sampled at 5, 50, and 95 cm below the water surface. For each zone the locations were numbered from 1 to 3 with 1 being the location furthest from the southern shore. The samplers were installed and positioned within the wetland using a GPS system, with locations 1 and 3 being approximately 25% of the width from the North and South shores, respectively, and location 2 positioned halfway between the shores. The plastic tubing from the samplers was immersed below the surface and held on the bottom of the wetland using steel weights located every 5 m along the bundle of tubing. All of the tubing from one emergent zone and one deep zone were brought to a single point and exited the wetland as a bundle that entered the large storage box con-

Table 1 – Selected physical characteristics of the 91st Ave. Trés Rios Hayfield site cell 1

	Value
Basin length (m)	228
Basin width (m)	60
Surface area (ha)	1.2
Ave. cross-sectional area (m^2)	35.2
Flow in (m^3 day^{-1})	1890
Flow out (m^3 day^{-1})	1470

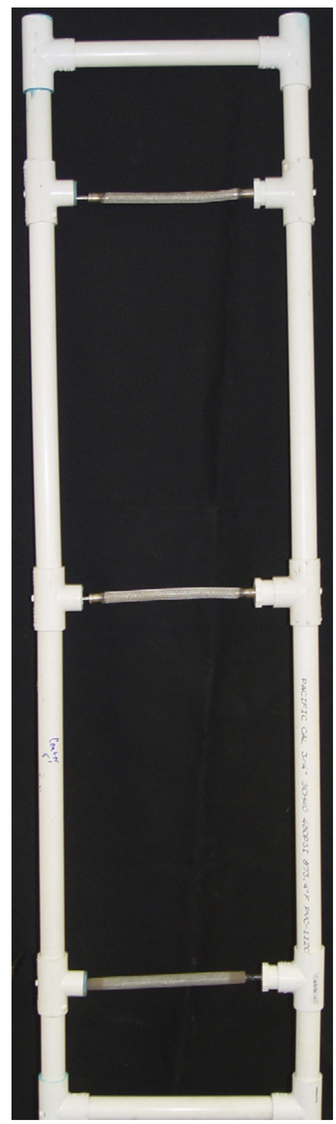

Fig. 3 – A photograph of a representative sample location with three sampling depths. The sample intake screens are mounted in a PVC frame. Low density polyethylene tubing will be connected to each sampler and passed through the left side of the frame. The frame can be anchored to the sediments by driving steel rebar down the pipe on both sides of the frame.

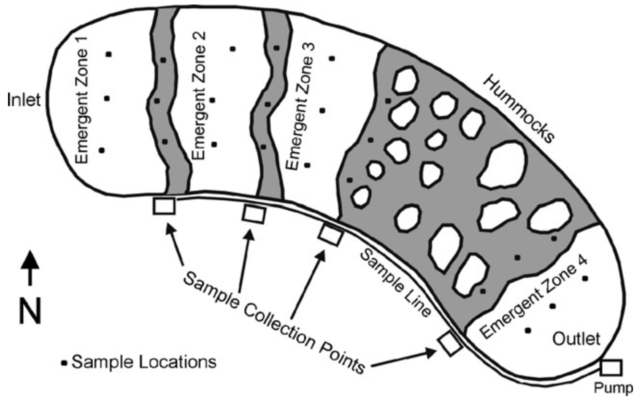

Fig. 4 – General layout of the 91st Ave. Trés Rios Hayfield site cell 1. There are four emergent zones and three deep-water zones. The third deep-water zone has 10 small and 5 large hummocks within it. The locations of the pump, sample collection points and each sample location are shown.

taining the manifold and rack to hold the sample collection bottles (Fig. 5). In all cases the storage boxes were located on the southern edge of the wetland. In between sampling events the glass bottles were removed and the stopper was placed in a piece of (3/4) in. schedule 40 PVC pipe (Fig. 2). The pipe was capped on one end and cut so that the long piece of plastic tubing just reached the bottom of the tube. In this configuration, the pump can be turned on and all of the plastic tubing can be rinsed with water from the wetland to clean out the water from the previous sampling event.

Each storage box was mounted in a steel frame and placed at the edge of the wetland in four different locations. Schedule 80 PVC pipe was laid from the pump at the outlet box to the sample boxes along the edge of the wetland. To minimize head loss the pipe was sized so that it decreased in size from 2.5 cm at the pump to 1.3 cm at the location furthest from the pump. A tee with a valve was placed at each storage box. A barbed nipple was placed after the valve to connect the manifold to the main suction line. This connection allowed the valve to

Fig. 5 – Sample collection point is shown with sample bottles during sample collection.

Fig. 6 – Pump set up at the outlet box of the wetland. The sample collection line is visible going off to the left of the intake line. The gate valve that is pointing up can be used to isolate the sample collection line from the pump.

be turned off and the tube connecting the suction line to the manifold to be secured inside the box. With this configuration the only part of the system exposed to the environment was the main suction line and the plastic tubing that was exiting the bottom of the box.

A pump with a suction head lift of 7.5 m and a capacity of 1000 L min^{-1} was chosen to provide sufficient suction at the most distant sampling location. The pump was installed in the outlet box of the wetland after the v-notch weir that determined the outflow of the wetland (Fig. 6). The pumped water was returned to the outlet box. This arrangement prevented the pump from affecting the hydrology of the wetland, but allowed the excess water drawn through the sample lines an outlet to the pump when sample bottles were full.

4. Sample collection

Initially the pump was primed and started with the sample line valve closed. After the pump was running the sample line valve was opened and the manifolds were connected to the main suction line and solution was drawn from the sample screens through the LDPE sample tube, through the PVC storage cells, and then out through the manifold and to the pump. To ensure that samples were representative of the wetland the sample lines needed to be thoroughly rinsed. The LDPE sample tube had an internal volume of 14.6 cm^3 per meter of tubing. The longest length of LDPE tubing used was 50 m resulting in a volume of 750 mL. To ensure complete rinsing of the sample tube the system was allowed to operate for at least 50 min. This allowed the stagnant water in the plastic lines to be rinsed out with greater than 10 rinse volumes. After rinsing, the PVC cells were replaced with the sample collection bottles (Fig. 5) and the bottles were allowed to fill for about 20 min. Using the individual valves, flow could be turned off to specific bottles and flow rates could be evened out. The flow rate to each individual bottle was maintained at approximately 150 mL min^{-1}. At this flow rate a non-turbulent zone was maintained around the sampler with a linear flux of 1.8 cm s^{-1} into the sample screen. When sample collection was complete, the suction was removed from all samples. The sample bottles were then removed from the stoppers and the PVC cells reattached for storage.

5. 3-D array evaluation

The sample array was tested over a 6-week period in April–May 2004. The test was a pulse addition of 200 kg of KBr to the inlet of the wetland over 30 min such that an inlet Br^- concentration of 100 mg L^{-1} was maintained. Samples were collected using the array over the next 6 weeks and analyzed for Br^- content. After collection the samples were returned to the lab for analysis. Samples were analyzed for bromide using suppressed ion chromatography with a carbonate/bicarbonate eluent. Data presented here is to validate that the sampling system is capable of providing discrete samples from 60 different locations

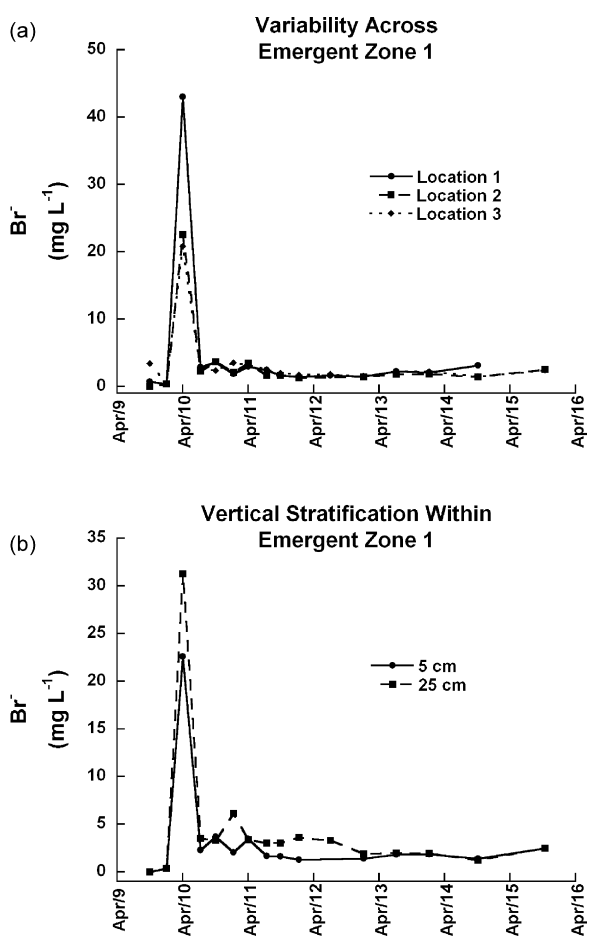

Fig. 7 – Bromide concentration from the surface samplers (a) collected from all three locations in emergent zone 1, and concentrations at two depths (b) from the middle location in emergent zone 1, for the 6 days following Br^- addition. It can be seen that location 3 is located within a zone that experienced higher Br-concentration than locations 1 and 2 and concentration stratification was observed at location 2. The array was able to sample spatial differences between locations and temporal patterns through time.

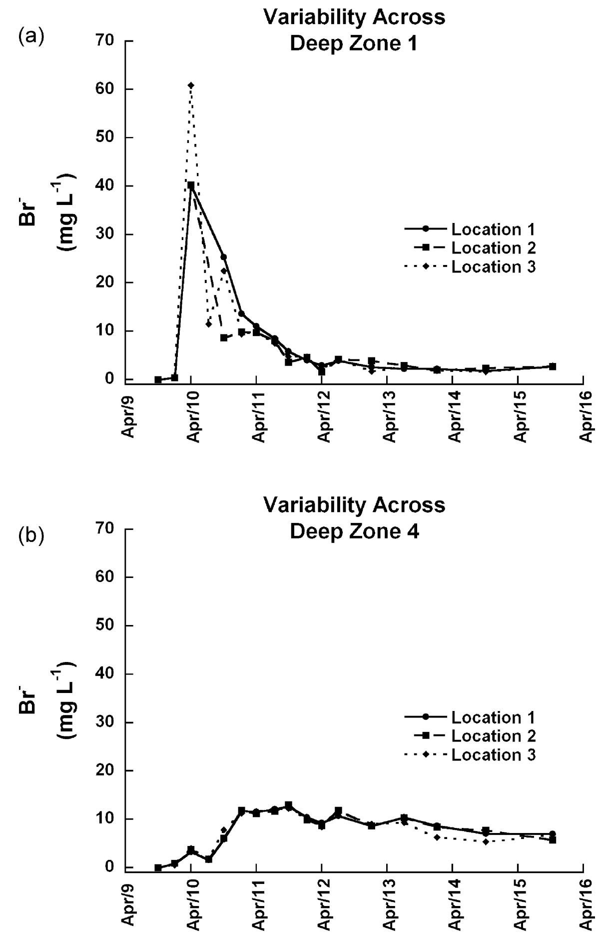

Fig. 8 – Bromide concentration from the surface samplers collected from all three locations in the deep-water zone containing the hummocks for 6 days following Br^- addition. Bromide concentration from all three locations prior to the hummocks (a) and post hummocks (b) is shown. The data demonstrates that the sampling array was able to show that the spatial concentration distribution perpendicular to the direction of flow was more uniformly mixed following the hummocks (b) than before the hummocks (a).

in a timely and cost-effective manner and that the system has utility for such things as internal hydraulic model calibration and characterization as well as long term monitoring.

The sampling array was evaluated in both deep and shallow zones. Results from the surface samplers in a shallow zone (emergent zone 1) for the first 6 days after Br^- addition are shown in Fig. 7a. As can be seen, samples collected from the sampling array show that internal differences in concentration across the emergent zone can be measured. For example, the midnight sampling on April 10 from sample location 3 (southern most location) was much greater than the concentration measured at the other two locations in the same zone. In this case the 3-D array demonstrated its utility by providing internal samples that showed higher Br^- concentrations in the southern portion of emergent zone 1 and similar Br^- concentrations at locations 1 and 2. Similar data could be useful in determining spatial differences in solute concentrations throughout the wetland. Additionally, Br^- concentration data from the middle sample location in emergent zone 1 (Fig. 7b) appear to show Br^- stratification similar to results previously reported (Sanford et al., 1995; Schmid et al., 2004).

Representative results from the deep zone sample locations are shown in Figs. 8 and 9. Differences in Br^- concentration can be seen across the wetland for the first 6 days following Br^- addition (Fig. 8). A single pulse of bromide passed by the surface of locations 1 and 2 within 12 h following Br^- introduction (Fig. 8a). At location 3, the same pulse was seen at 12 h, followed by a smaller secondary pulse reaching the sensor about 24 h after Br^- addition. This indicates that the array was able to detect that Br^- traveled along at least two distinct flow paths since a single pulse entered the wetland and arrived at location 3 in two pulses 12 h apart. Fig. 8b also shows that by the time the water reached deep zone 4 near the outlet, mixing had removed most of the variation in Br^- concentration across the wetland.

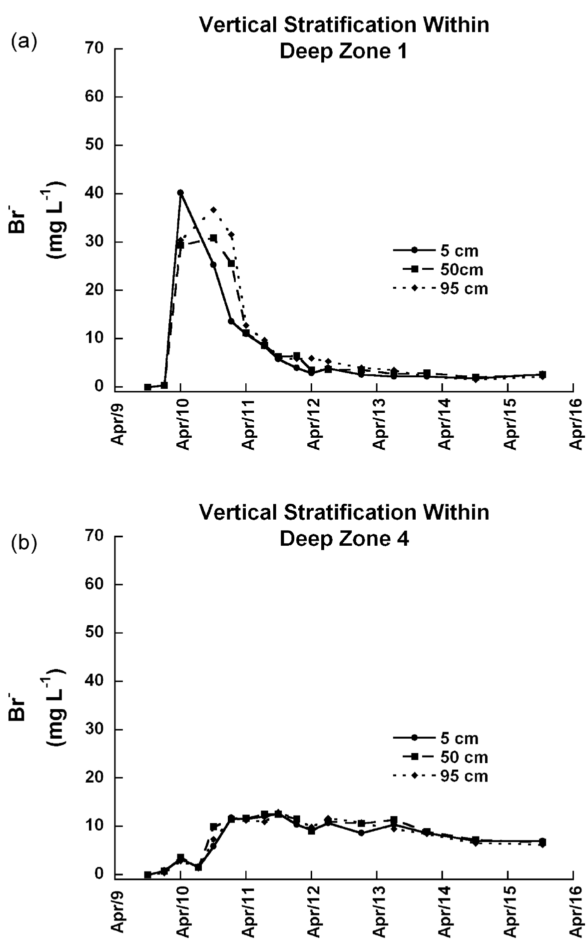

Fig. 9 – Bromide concentration from all depths collected from location 1 prior to and following the hummocks for the first 6 days following Br^- addition. Bromide concentration at each depth prior to the hummocks (a) and post hummocks (b) is shown. Comparison of the two locations shows that prior to the hummocks there was concentration stratification (a) with the surface having a concentration more than three times higher than at a depth of 95 cm, however after the hummocks there was no evidence of concentration stratification.

In addition, Br^- concentrations from the same horizontal location but at different depths are also observable (Fig. 9). The Br^- concentrations for the first 6 days from the surface samplers at location 1 in deep zone 1 (Fig. 9a) and location 1 in deep zone 4 (Fig. 9b) show that the 3-D array can be used to better estimate and model the wetland hydrology and degree of vertical mixing within the wetland. The highest concentration of Br^- 5 cm below the water surface at location 1 in deep zone 1 occurred 12 h following Br^- addition, but for the samples taken from 50 and 95 cm below the surface the maxima occurred 18 h following Br^- addition. By deep zone 4 the vertical stratification is no longer present (Fig. 9b). High-intensity sampling made possible by the 3-D array could be integral in understanding design features intended to increase vertical mixing within the wetland.

The 3-D array was used successfully to sample the wetland at 60 different points in the wetland throughout a 6-week period over which time only one major problem was observed. The plastic tubing leaving the storage boxes was an attractant for chewing by rodents and other animals, and as a result some of the tubing that was exposed above the water line was damaged and allowed air to enter the sample tube during operation. To fix this problem the tubing was replaced and then bundled together and placed inside flexible conduit from the storage box to below the water line. Since placing the tubing in the conduit no further problems have been documented.

6. Conclusions

A new relatively low-cost sample collection design has been developed using mostly off-the-shelf parts that allows for permanent, internal, three-dimensional sample collection in wetlands. The design has been used to construct a permanent 3-D array of 60-sample locations for less than US$ 5000. The array has been used to sample at each location individually or simultaneously in a 1.2 ha constructed wetland. The design offers significant cost savings to traditional sampling techniques. Previously published studies have included up to 26 sampling locations throughout a wetland (Dierberg et al., 2005; Martinez and Wise, 2003). Typical automated samplers will cost US$ 1,000–3,000 each, resulting in an initial capital expenditure of US$ 26,000–78,000. The system described here is expandable and the principle cost is associated with the purchase of the pump (US$ 1500) and groundwater sampling screen (US$ 32/ea) resulting in a cost of US$ 2500. In addition to the pump and screens the PVC pipe and miscellaneous fittings for the described system would be less than US$ 1000. The LDPE tubing is priced at US$ 0.15/m, which would provide 10,000 m of tubing for the system and a total cost of US$ 5000 resulting in a savings of 80%.

The three-dimensional sample array described here is cost-effective, simple to operate and robust for high intensity internal sampling of wetlands and other water bodies. Internal sampling will be useful in investigating the internal hydraulics and biogeochemistry of wetlands and other water bodies (Zhou and Hosomi, 2008; Lightbody et al., 2007; Hernandez and Mitsch, 2007; Gottschall et al., 2007; Moreno et al., 2007). The most important consideration when designing the system is ensuring that the pump is sized large enough that when the sample bottles are filling the air that enters, the system will not cause the system to lose prime. In addition, it is important that the materials used in the design are well suited to the experimental objectives. The use of plastic in the sample collection tubing would not be a good choice to sample for compounds that were known to adsorb to low density polyethylene; however, this problem can be overcome through the use of Teflon or some other non-adsorbing material. This would significantly increase the cost of the system; however, the same design criteria can be used.

This system has a wide range of useful applications in environmental monitoring and experimentation in bodies of water. The 3-D array can help researchers better understand flow through bodies of water as well as it can be used for long term monitoring and environmental fate of constituents within water bodies. Due to natural fluctuations in inflow to bodies of water, the monitoring of inflow and outflow for constituents of interest may not be monitoring the same volume of water. This would mean that a reduction in concentration of a particular compound from inflow to outflow may not be due to transformation within the system but instead may be due to measuring a different volume of water that was simply lower in concentration. The internal sampling array will allow for following a constituent through a body of water to determine where transformations occur.

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